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EXTENDED GAUGE SECTORS *†

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ABSTRACT

Present and future prospects for the discovery of new gauge bosons, Z' and W', are reviewed. Particular attention is paid to hadron and e^+e^- collider searches for the W' of the Left-Right Symmetric Model.

1. Introduction

An extension of the gauge sector of the Standard Model(SM) would not only lead to the existence of new gauge fields, but will almost always require the introduction of exotic fermions[1] to cancel anomalies as well as new Higgs fields[2] to break the extended gauge symmetry. In addition, GUT scenarios leading to gauge extensions require the existence of SUSY in order to maintain the hierarchy of breaking scales and obtain coupling constant unification. Thus the phenomenology of extended gauge models(EGM) is particularly rich as is indicated by the rather extensive literature on this subject. Unfortunately, this implies that there are an enormous number of interesting models currently on the market which means that any overview of the subject is necessarily incomplete. Hence, we will be forced to limit ourselves to a few representative models and restrict our discussion to searches for new gauge bosons at hadron and e^+e^- colliders[3]. Regrettably, this leaves vast and fascinating territories untouched.

In what follows, we chose as examples the set of models recently discussed by Godfrey[4] so that we need say little here about the coupling structure of each scenario; curious readers are requested to consult Godfrey's paper and references therein for the details of each model. To be specific, we consider (*i*) the E_6 effective rank-5 model(ER5M), which predicts a Z' whose couplings depend on a single parameter $-\pi/2 \leq \theta \leq \pi/2$ (with models ψ, χ, and η denoting specific θ values); (*ii*) the Sequential Standard Model(SSM) wherein the new W' and Z' are just heavy versions of the SM particles (of course, this is not a true model in the strict sense but is commonly used as a guide by experimenters); (*iii*) the Left-Right Symmetric Model(LRM) and, lastly, (*iv*) the Alternative Left-Right Model(ALRM), arising from E_6, wherein the fermion assignments are modified in comparison to the LRM. In the ALRM, the W' carries lepton number so that it cannot be produced via the ordinary Drell-Yan pro-

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cess but only in association with a leptoquark thus making it difficult to observe over top quark backgrounds at hadron colliders. The LRM owes much of its survival over the last two decades to the plethora of free parameters it contains: (a) the ratio of the gauge couplings, $0.55 \leq \kappa = g_R/g_L \leq 2(naturalness??)$, the lower limit being forced upon us by the internal consistency of the model; (b) the masses of the right-handed(RH) neutrinos, (c) the elements of the RH CKM mixing matrix, V_R, which are *a priori* different than V_L, and (d) the W_R-Z_R mass relationship,

$$\frac{M_{W_R}^2}{M_{Z_R}^2} = \frac{(1-x_w)\kappa^2 - x_w}{\rho_R(1-x_w)\kappa^2} \tag{1}$$

where x_w is the usual weak mixing angle and the parameter ρ_R takes on the value 1(2) if the $SU(2)_R$ breaking sector consists solely of Higgs doublets(triplets). (The triplet scheme is favored in the see-saw scenario for neutrino masses.) From this we see that unless the $SU(2)_R$ breaking sector is somewhat unusual, the Z_R will always be more massive that the W_R. This large set of parameters will return to haunt us when we examine W_R searches.

2. Z' : Then and Now

Since Z' searches have been discussed by many authors[4], our overview of this subject will be quite brief. At present, the Tevatron provides the best direct search limits for new gauge bosons[5], corresponding to 505 GeV for the Z' (and 652 GeV for the W') of the SSM, from the run Ia electron data sample. Figs.1a-c show how the Z' search reach of the Tevatron should evolve with time for several different models assuming no new particles are discovered; including μ's in the data sample should increase all of the results shown by $\simeq 35-40$ GeV. In all cases, we assume that the Z' decays to only SM fermions and Z-Z' mixing is neglected. Apart from these assumptions, the limits depend only upon a single parameter, θ in the ER5M and κ in the LRM. Pushing the Tevatron luminosity, L, up above 1 fb^{-1} implies that Z' masses of order 1 TeV are beginning to be probed. Figs.1d-f show the corresponding (electrons *only*!) results for the LHC(with $\sqrt{s}$ =14 TeV) and the influence of additional decay modes on the search reach, *i.e.*, decreasing the leptonic branching fraction of the Z' by a factor of 2 reduces the reach by $\simeq 0.33$ TeV. For LHC luminosities above 100 fb^{-1}, Z' masses in excess of 4 TeV become accessible. At the NLC, Z' searches are performed by looking for systematic shifts in multiple observables, making full use of the anticipated high electron beam polarization. A 500 GeV machine with L=50 fb^{-1} probes Z' masses in the 1.5-5 TeV range[4], which nicely complements the direct production searches at the LHC. A machine with four times this energy and luminosity may extend this reach

by a factor of 3-4.

3. W' : Hadron Collider Search Caveats

Unlike Z' searches at hadron colliders, the corresponding W' searches via the Drell-Yan process have many subtleties; this is most easily demonstrated within the LRM context[6]. The CDF W' search assumes that the $q'\bar{q}W'$ production vertex has SM strength (*i.e.*, (*i*) $\kappa = 1$ and (*ii*) $|V_{L_{ij}}| = |V_{R_{ij}}|$), that the RH neutrino is (*iii*) 'light' and 'stable', appearing as missing E_T in the detector, and that the W_R leptonic branching fraction(B_l) is the SM value apart from contributions due to open top(*i.e.*, (*iv*) no exotic decay channels are open). If any of these assumptions are invalid, what happens to the search reach? Assumptions (*i*) and (*iv*) are easily accounted for by the introduction of an effective κ parameter, $\kappa_{eff} = \kappa\sqrt{B_l/B_l^{SSM}}$ which simply adjusts the overall cross-section normalization with the resulting reach shown in Fig.2a. If assumption (*ii*) is invalid, a significant search reach degradation[6] occurs as is shown in Fig.2b for CDF run Ia; *e.g.*, one finds via a Monte Carlo study that for 50(10)% of the V_R parameter space the Tevatron run Ia W_R reach is reduced to less than 550(400) GeV. This reduction is a result of modifying the weight of the various parton luminosities which enter into the calculation of the cross-section. At the LHC, surrendering (*ii*) does not cost us such a large penalty since the W_R production process occurs through the annihilation of sea$\times$valence quarks in pp collisions, whereas it is a valence$\times$valence process at the Tevatron. From Fig.2c we see that varying V_R modifies the reach no more than 20%. Life gets *much* harder if ν_R does not appear as missing E_T. A massive ν_R will most likely decay within the detector to $\ell^\pm + jj$, with either charge sign equally likely if ν_R is a Majorana fermion. A parton level analysis of this scenario has been carried out by Datta *et al.*[7] for the LHC; they find a 'viable signal' for W_R masses below 2-3 TeV for the entire $m_{\nu_R} < M_{W_R}$ range. (This analysis needs to be repeated including a full detector simulation and should also be done for the Tevatron.) Perhaps the worst case scenario is when ν_R is more massive than W_R so that W_R has only hadronic (or exotic) decay channels open. Can W_R be seen as a bump in dijets? Clearly the chances are somewhat better at the Tevatron where S/B is perhaps manageable given reasonable statistics; CDF has already performed such an analysis with run Ia data[8] with somewhat limited results. At the LHC, where the dijet backgrounds have increased enormously due to the rise in the glue-glue luminosity, a preliminary study by the ATLAS Collaboration indicates that such dijet searches might still be possible provided excellent energy resolution is available[8]. More analysis is necessary to clarify this case.

Additional help in such a pessimistic situation may be provided by the LRM's W_R-Z_R mass relationship, *i.e.*, if a Z_R is found but $m_{\nu_R} > M_{W_R}$, this relation tells us something about *where* to look in dijets for the W_R. If, instead, only a limit on the Z_R mass is obtained, the same mass relation can be used to get a relatively weak (but

conservative!) limit on the mass of W_R. Figs.2e-f show the result of this approach for the Tevatron using the curves in Fig.1b as input. Note the indirect limit on the W_R mass from run Ia with $\kappa = 1$ is only 270 GeV assuming triplet $SU(2)_R$ breaking, which is only about 45% of the canonical SSM value. When the integrated L increases to 1 fb^{-1}, this bound grows to only 450 GeV. This indirect limit is substantially larger at the LHC, as shown in Fig.2f, but is still less than 50% of the usually claimed reach. Note that this limit is reasonably sensitive to the nature of $SU(2)_R$ breaking but somewhat less sensitive as to whether the Z_R has exotic decay modes. If dijet W_R searches are impossible in practice, we need to turn to other production strategies.

4. W_R's at the NLC

The NLC can also play a crucial role at unraveling the charged-current sector of EGM's. W_R production in e^+e^-, γe, and e^-e^- collisions [9] is insensitive to V_R and scales simply with κ thus immediately avoiding two of the above difficulties with hadron collider searches. All three processes can yield valuable information about both W_R and the mass spectrum of the LRM. Note that the like-sign e^-e^- process *only* occurs when ν_R is a Majorana fermion. In addition, due to the relatively clean environment and high beam polarization, signatures are also easier to spot and backgrounds are readily reduced. Unfortunately, the sensitivity to $m_{\nu_R}(= M_N)$ remains at some level in all cases and a dependence on the doubly-charged Higgs mass, M_Δ, occurs in the e^-e^- case.

W_R pair production occurs with a large σ yielding more that 10^4 events up to the kinematic limit as shown in Figs.3a-b; increasing the ν_R mass in the t-channel graph generally reduces σ near threshold, where σ is largest, and flattens the angular distribution. For large $\sqrt{s}$ it delays the unitarity cancellation between the amplitudes resulting in a bigger σ. Since the Z_R mass is less than twice that of W_R for most parameter values, σ does not show much sensitivity to the possible variations in M_{Z_R}. For reasonable L's, $W_R(W_R)^*$ production allows for searches up to $M_R \simeq 0.8\sqrt{s}$. At the tree level, the W_R pair cross-section is insensitive to the Dirac or Majorana nature of the RH neutrino.

The single production of W_R's in association with ν_R in γe collisions via laser backscattering has been re-analyzed recently by Raidal[9] taking into account both e and γ beam polarization. Essentially the entire kinematic region is found to be accessible with polarization playing an important role in identifying the signal and reducing backgrounds.

The $e^-e^- \to W_R^-W_R^-$ lepton-number violating process is perhaps the most interesting way of looking for W_R's as both the Majorana nature of $\nu_R(N)$ and the $SU(2)_R$ symmetry breaking are probed simultaneously. The helicity-amplitude analysis for like-sign production has recently been performed by Helde *et al.*[9]. As shown there, as well as in previous analyses(see Figs.3c-d), the cross-sections are quite large but

reasonably sensitive to both $M_{N,\Delta}$ variations. As a whole, larger values of M_N yield larger rates whereas the cross-section vanishes as $M_N \to 0$. It has recently been shown that allowing for one of the W_R's to be off-shell still yields a reasonable rate for W_R masses as large as $0.8\sqrt{s}$(see Figs.3e-f). This analysis assumed that only the jj decay modes of the W_R were accessible thus allowing for the possibility of $M_N > M_R$. In either case, the W_R angular distribution is found to be relatively flat implying that acceptance cuts will not have any substantial impact on rates.

5. References

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Fig. 1. Tevatron search reach for the Z' in the (a)ER5M and (b)LRM for run Ia(lower curves, MRSA pdf's are dashdots while CTEQ3M pdf's are solid) and with increased L's of 100, 250, 500, and 1000 pb^{-1}(from bottom to top). (c)L dependence of Tevatron search reach for the ALRM(dashdot), SSM(dots), LRM with $\kappa = 1$(dashes), and ψ(solid) Z''s. (d) and (e) are the same as (a) and (b) but for the LHC with 100 fb^{-1}; the lower curve corresponds to a reduction of the naive leptonic branching fraction by a factor of 2. (f)Same as (c) but for the LHC.

Fig. 2. (a)Tevatron W_R reach as a function of κ_{eff} as described in the text for the same L values as in Fig.1a. (b)Percentage of the V_R parameter space allowing the W_R below a given value from run Ia. (c)Maximum and minimum cross-sections for W_R production at the LHC due to V_R variations for $\kappa = 1$. Indirect W_R search limits for the Tevatron (d)run Ia and with (e)L=1 fb^{-1} as well as (f)for the LHC. Doublet(triplet) $SU(2)_R$ breaking corresponds to the dotted(dashdotted) curves. In (f), the lower curves correspond to a factor of 2 reduction in the Z' leptonic branching fraction.

Fig. 3. (a)W_R pair production cross-section vs. M_N at a 1.5 TeV NLC assuming κ=1 and M_R=700 GeV. (b)Same as (a) but vs. $\sqrt{s}$ assuming M_N=100(500,1000,2000) GeV corresponding to the dotted(dashed,dashdotted,solid) curve. Cross-section for like-sign W_R production with $\sqrt{s}$=1 TeV as a function of (c)M_N and (d)M_Δ for κ=0.9 and M_R=480 GeV. In[(c),(d)], the curves on the right(left)-hand side correspond, from top to bottom, to M_Δ=800,1200,500,1500,200, and 2000 GeV [M_N=1500,1200,800, 500, 200 GeV]. Event rates per 100 fb^{-1} for W_R+jj production at a 1.5 TeV e^-e^- collider assuming $\kappa = 1$ and M_R=1 TeV (e)as a function of M_N for M_Δ=0.3(0.6,1.2,1.5,2) TeV corresponding to the dotted(dashed, dash-dotted, solid, square-dotted) curve; (f)as a function of M_Δ for M_N=0.2(0.5,0.8,1.2,1.5) TeV corresponding to the dotted(dashed, dash-dotted, solid, square-dotted) curve.